Vertical Datum Conversions for Regional Coastal Management

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Abstract

Transforming surveyed elevations and water depths to desired vertical datums is an essential step in building a regional coastal management plan. Regional coastal management plans are based on sediment volume changes and numerical simulations of regional coastal change. Computation of sediment volume changes are possible only if the survey data sets compared share the same vertical datum. Some numerical simulations of regional coastal change require a baseline data set that is referenced to a particular stage of the tide. Until recently, hydrographic and topographic surveys covered areas that were sufficiently small to require only a simple vertical shift to convert the survey data to the desired vertical datum based on local established benchmarks. Data sets that cover large areas are now available through rapid survey techniques like airborne lidar, and through digital publishing of data, like that found on nautical charts. These data sets are not easily converted to a common datum. The magnitude of this problem for regional applications is being recognized only now. The vertical location of tidal, geodetic, and ellipsoidal datums can vary widely over the large areas that these data sets cover. The datums are derived at discrete points distributed sparsely through an area. This paper outlines methodologies for developing and applying regional datum conversions. The methods presented are designed both to realistically represent vertical datums as surfaces instead of discrete points within a region and to minimize error in volume computations and numerical simulations for regional coastal management.

1.0 Introduction

Transforming elevation and depth data to desired vertical datums is a step in the process of performing coastal surveys. The raw data are collected relative to different vertical planes depending on the type of survey being performed. For the United States and Canada, upland rod and transit surveys are generally collected relative to a network of benchmarks whose vertical positions are referenced to the North American Vertical Datum of 1988 (NAVD88). NAVD88 is based on a geopotential surface that represents MSL. This surface is constrained to the actual value of MSL at Father Point/Rimouski, Quebec, Canada. NAVD88 supercedes the National Geodetic Vertical Datum of 1929 (NGVD29). NGVD29 is also based on the geopotential surface that represents mean sea level, but for NGVD29, the surface was constrained to the value of mean sea level at 26 tide stations along the North American coast (NOAA 2000a). In the US, the network of benchmarks are established, updated, and maintained by the National Geodetic Survey (NGS), a part of the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA).

Hydrographic survey data collected from vessel-borne sonar or airborne lidar are referenced to the water surface. Depths are determined relative to tide measurements obtained during the survey. The tide gauge is referenced to a tidal benchmark. In the US, tidal benchmarks are established, updated and maintained by NOS. Tidal datum elevations are determined for each benchmark by comparison of measurements recorded simultaneously at a tide gauge local to the benchmark, and a gauge that has datum elevations established based on 19 years of tidal data. The typical tidal datums included are: mean lower low water (MLLW), mean low water (MLW), mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW). The tidal benchmarks are tied into the geodetic benchmark network using differential leveling or GPS occupation of the station for an extended period of time (NOAA 2000a). A graph relating each these surfaces to MLLW at East Pass, Florida, is shown in Figure 1.1.

Recently, kinematic GPS has enabled raw sounding data collection relative to an ellipsoid, which is a mathematical representation of the earth's surface. While data collection using this technology eliminates reliance on tidal or geodetic datums, vertical datum conversions are required to conform to datum specifications for each survey and to perform comparisons with historic data sets.

Vertical datum conversions for land surveys and traditional hydrographic surveys are simply accomplished by applying a single vertical correction for a small survey area. The correction is computed from elevation differences established for local benchmarks. If the data set covers an area in which there are multiple benchmarks, a correction may be established and applied for each one based on the proximity of each data point to particular benchmarks. In this case, a survey is divided into sub-areas, with differing corrections applied in each.

Advances in survey technology have introduced new challenges for performing vertical datum conversions. Airborne lidar bathymeters and multibeam fathometers collect depth information that is very dense horizontally. If a very dense data set covers areas in which there are multiple benchmarks,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Vertical Datum Conversions for Regional Coastal Management**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Engineer District Mobile,109 St. Joseph Street,Mobile,AL,36602**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

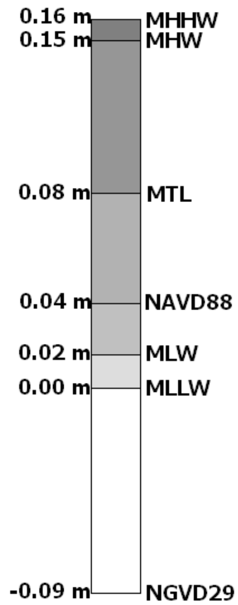

Figure 1.1 Datum elevations relative to MLLW at East Pass, Florida (after NOAA 2000b and NOAA 2000c).

multiple vertical corrections may be applied as described above. This causes obvious "steps" in elevation at the interfaces of the areas designated for each benchmark. This is not typically the case with sparsely collected data. The larger distances between sparsely collected data mask these "steps." While the "steps" are still present in the survey, they are not as evident as in a densely collected data set.

An additional challenge arises with the maturation of airborne lidar technology. The speed of these systems enables surveys of very large areas over a very short time period. This often includes long stretches of coastline where no, or only a few benchmarks have been established. In this situation, vertical datum conversions must be developed with little knowledge regarding the regional variability of the datum surfaces involved in the conversion.

The difficulty in transferring vertical datum conversions to a regional scale data manipulation scheme was encountered during development of a baseline data set for the US Army Corps of Engineers (USACE), Mobile District, Regional Sediment Management (RSM) Demonstration Program. The RSM Program was initiated in recognition of the interaction of engineered navigation and beach restoration projects with adjacent coastal projects. Advances in computer technology have just recently made this type of program feasible with the capability to manage and manipulate large data sets in GIS and with the increasing computer power required to drive regional scale models. This paper outlines the RSM Program data requirements and presents the regional vertical datum conversion problem and the scheme used to create the baseline data sets.

2.0 RSM Demonstration Program

2.1 Introduction

The goal of the RSM Demonstration Program is to develop a project management approach in which each navigation and beach restoration project is considered a single component of an interacting system (Lillycrop 2000). This approach allows greater flexibility for management at individual projects. For example, the impact of navigation channels on adjacent shorelines has long been recognized. However, regulations may not allow for disposal of dredged material on these shorelines. In a regional management scheme, disposal of dredged material on the adjacent beaches is often logical, because the beaches and longshore transport are the source of the dredged sand originally. For the case of beach restoration projects, large amounts of sand are placed on the beach. The sand will eventually wash into adjacent navigation channels. A model estimating the rate of channel shoaling caused by the beach restoration project can provide guidance for planning the time interval between dredging episodes.

The approach for reaching a regional management scheme for the RSM Demonstration Program comprises two main parts, both manipulated using GIS: the collocation and comparison of historical data sets and the creation of tools to forecast future changes. Both of these components require a baseline of current conditions from which to calculate historical sand volume changes, and from which to predict future changes. The sand volume changes computed from historical data sets are used to calibrate the numerical models that comprise the forecasting tools.

The RSM demonstration region encompasses 360 kilometers of Gulf of Mexico shoreline stretching from the west end of Dauphin Island, Alabama, USA, east to Apalachicola Bay, Florida, USA (Figure 2.1).

2.2 RSM baseline data set

The RSM baseline data set contains the most recent elevation data for every part of the demonstration region. This "most recent" dataset includes three types of hydrographic and topographic data: singlebeam fathometer data, multibeam fathometer data, and airborne lidar bathymetry and topography.

2.2.1 NGDC nautical chart data

The most extensive data set (in area) used to create the RSM baseline data set was obtained from National Geophysical Data Center (NGDC). These data are the data that appear on NOAA nautical charts and are the result of several years of hydrographic surveying. The NGDC data is referenced to MLLW based on NOAA specifications

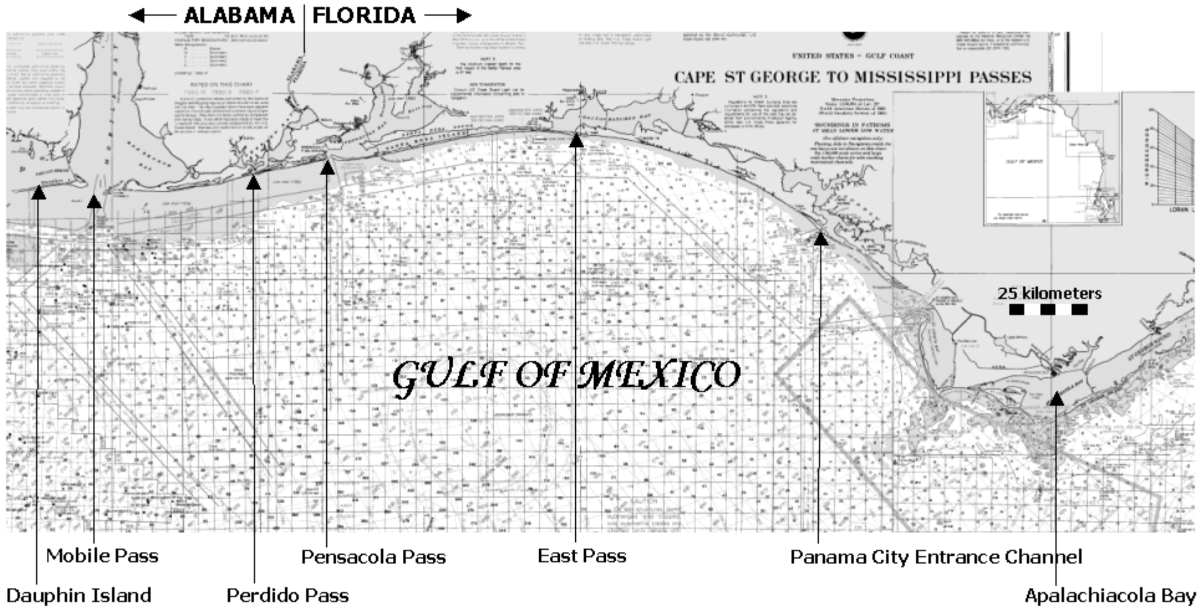

Figure 2.1 RSM Demonstration Program Region.

that require transfer of tidal datum based on comparisons of simultaneous tide measurements collected at a gauge near the survey site and an established gauge (NOAA 1999). These data cover the nearshore of the region represented in Figure 2.1. In most areas, the distance between adjacent points ranges from 300 meters near shore to 1500 meters farther offshore. Exceptions are the navigation channels at Mobile Pass, Alabama, Pensacola Pass, Florida, and the Panama City Entrance Channel, Florida (Figure 2.1). In these areas the data density approaches 30 meters.

2.2.2 Navigation channel condition surveys

The US Army Engineer District (USAED) Mobile's Irvington Site Office provided the second type of data included in the RSM baseline data set. The data take the form of navigation channel condition surveys collected using a singlebeam fathometer. This type of data was included in the baseline for Mobile Pass and Perdido Pass, both located in Alabama (Figure 2.1). These data were originally referenced to MLLW using tidal gauges at the passes. The survey coverage includes only the authorized navigation channel, with data points collected in profile lines spaced approximately 100 meters apart along the length of the navigation channel. Data spacing along the profile lines is sub-meter. These data were collected in Spring of 2000.

2.2.3 SHOALS data sets

The final type of data included in the RSM baseline is that collected by the USACE SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system (Lillycrop et al. 1996). These data were collected at a density of 4 meters for project condition surveys at East Pass, Pensacola Pass, Panama City, and Perdido Pass. The surveys were collected for USAED Mobile. Survey coverage includes the navigation channel, ebb and flood shoals, and adjacent shorelines and offshore areas. For these surveys, depth data were collected relative to the water surface and were referenced to tidal gauges in each of the inlets. The tidal gauges were set relative to NOAA tidal benchmarks in the area.

In addition to the SHOALS project condition surveys, SHOALS shoreline surveys were also included in the RSM baseline data set. SHOALS data have been collected for the entire coastline of the RSM demonstration region. The Florida Department of Environmental Protection (FLDEP) commissioned SHOALS data extending from the Panama City Entrance Channel to Apalachicola Bay, Florida (Figure 2.1) to support monitoring of coastal erosion. The data were collected relative to a short baseline of NOAA benchmarks relative to NGVD29 using kinematic GPS. The remaining coastline was surveyed by SHOALS as part of the RSM initiative. These data were collected relative to the water surface and were referenced to tidal benchmarks in the area by interpolation between them. These last two data sets were collected at a density of 8 meters. The surveys follow the coastline, covering 150 meters of inshore dry beach and 400 meters of offshore bathymetry.

2.2.4 Merging data sets

As mentioned above, the baseline data set represents the most recent data for each part of the

demonstration region. This means data collected most recently for each area supercedes all other data for that area. For example, near East Pass, Florida, the most recent data set includes NGDC data, the RSM SHOALS shoreline data set (collected in 2000), and a SHOALS project condition survey (collected in 1997). The NGDC data is superceded by the more recent SHOALS surveys. So, the NGDC data retained for the RSM baseline data set only covers the offshore areas beyond the extent of the SHOALS surveys. The SHOALS project condition survey of 1997 includes data for the flood and ebb shoals, adjacent beaches and inlet throat at East Pass. The RSM SHOALS shoreline data set collected in 2000 covers an area along the shoreline extending from 300 meters onshore to 800 meters offshore. The 2000 data set supercedes the 1997 data set in this alongshore swath. The 1997 data for the flood and ebb shoals and inlet throat that lie outside of this swath are retained for the baseline data set.

A graphical representation of the data retained in the RSM baseline data set is shown in Figure 2.2. The triangles shown in Figure 2.2 represent individual NGDC data points, while the 4- to 8-meter density SHOALS data sets are represented by filled polygons.

3.0 Vertical datum conversions

The task of creating a baseline, or “most recent” data set required conversion of each of the data sets to a common datum. To conform to GIS standards of the FLDEP, a partner in the RSM Program, the common datum chosen for the RSM GIS was NAVD88. The tidal and sediment transport models for which the baseline data sets serve as the initial condition require that the elevations and depths be referenced to MTL.

3.1 Small data set conversions

For the smaller data sets, the conversions were accomplished by a simple vertical adjustment. The smaller data sets are those collected using singlebeam fathometers and the SHOALS system at a single inlet location, i.e. Perdido Pass, Pensacola Pass, East Pass, and Panama City Entrance Channel. The largest of these surveys, at East Pass, Florida, covers less than 5 kilometers in both the across-shore and alongshore directions. The vertical adjustments were computed by tidal datum differences published on NOS tidal benchmark sheets (NOAA 2000b), or related geodetic heights published by NGS (NOAA 2000c).

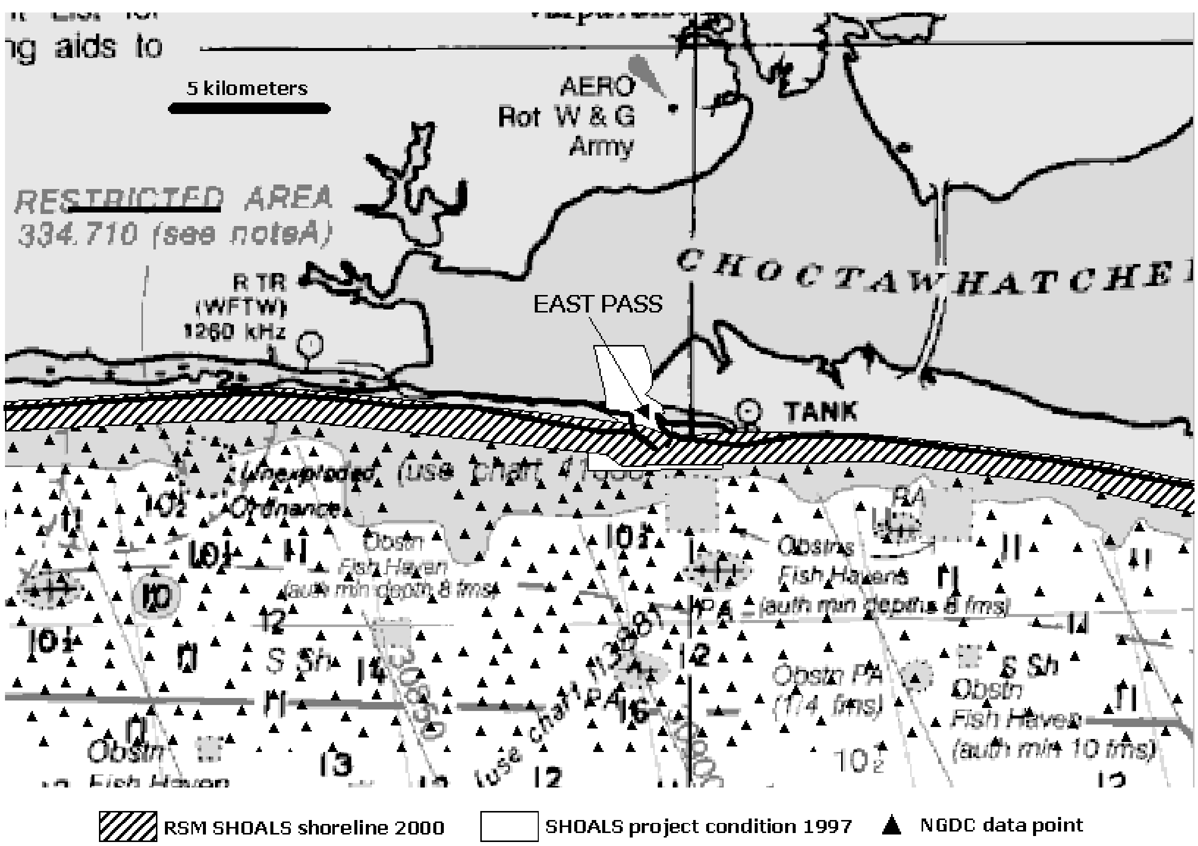

Figure 2.2 East Pass, Florida. Graphical representation of data retained for RSM baseline data set. Triangles represent actual NGDC data points while SHOALS 4- to 8-meter density data sets are represented by filled polygons.

For example, at East Pass, Florida, the original SHOALS data set was referenced to MLLW. According to the tidal benchmark sheets published by NOS on the World Wide Web, the difference between MTL and MLLW is 0.08 meters (Figure 1.1). The conversion from MLLW to MTL requires a simple subtraction of 0.08 meters from all the soundings collected in the survey. For example, a measurement that has an elevation of –1.00 meters when referenced to MLLW has an elevation of –1.08 meters when referenced to MTL. This is because the datum surface MTL is above the datum surface MLLW, so the conversion to MTL makes depths deeper and elevations lower. The conversion from MLLW to NAVD88 is very similar. The tidal benchmark height relative to MLLW obtained from the NOS published benchmark sheets is 8.00 meters. The tidal benchmark height relative to NAVD88 from NGS is 7.96 meters. So at East Pass, NAVD88 is above MLLW, and the conversion is a subtraction from the soundings of the height difference between the two datums, or 0.04 meters (Figure 1.1).

3.2 Large data set conversions

Creating a vertical datum conversion for the larger data sets introduced the challenge mentioned above: creating a seamless transformation for very dense data sets with very sparse information regarding the regional variability of the datum surfaces. The larger data sets are the NGDC data set and the SHOALS shoreline data sets collected for the FLDEP and the RSM Program. Two methods were developed for converting between vertical datums. The first involves linear interpolation between known points and the second involves modeling a regional tide.

3.2.1 Linear interpolation between known points

Datum elevation values are defined at only 100 discrete points throughout the RSM region. Some of these points are located in backbay areas and do not accurately represent the tidal datums on the open coast where the majority of the RSM data were collected. In the top portion of Figure 3.1 the locations of backbay benchmarks within the region are marked with an '**x**' and the locations of open coast benchmarks are marked with a '●'. Note that the majority of the benchmarks are established in locations where navigation is of great import—at the inlets. The graph in the lower portion of Figure 3.1 shows the difference between MLLW and NAVD88 for each established tidal benchmark. The vertical lines connect the benchmark locations with their difference values for the open coast benchmarks.

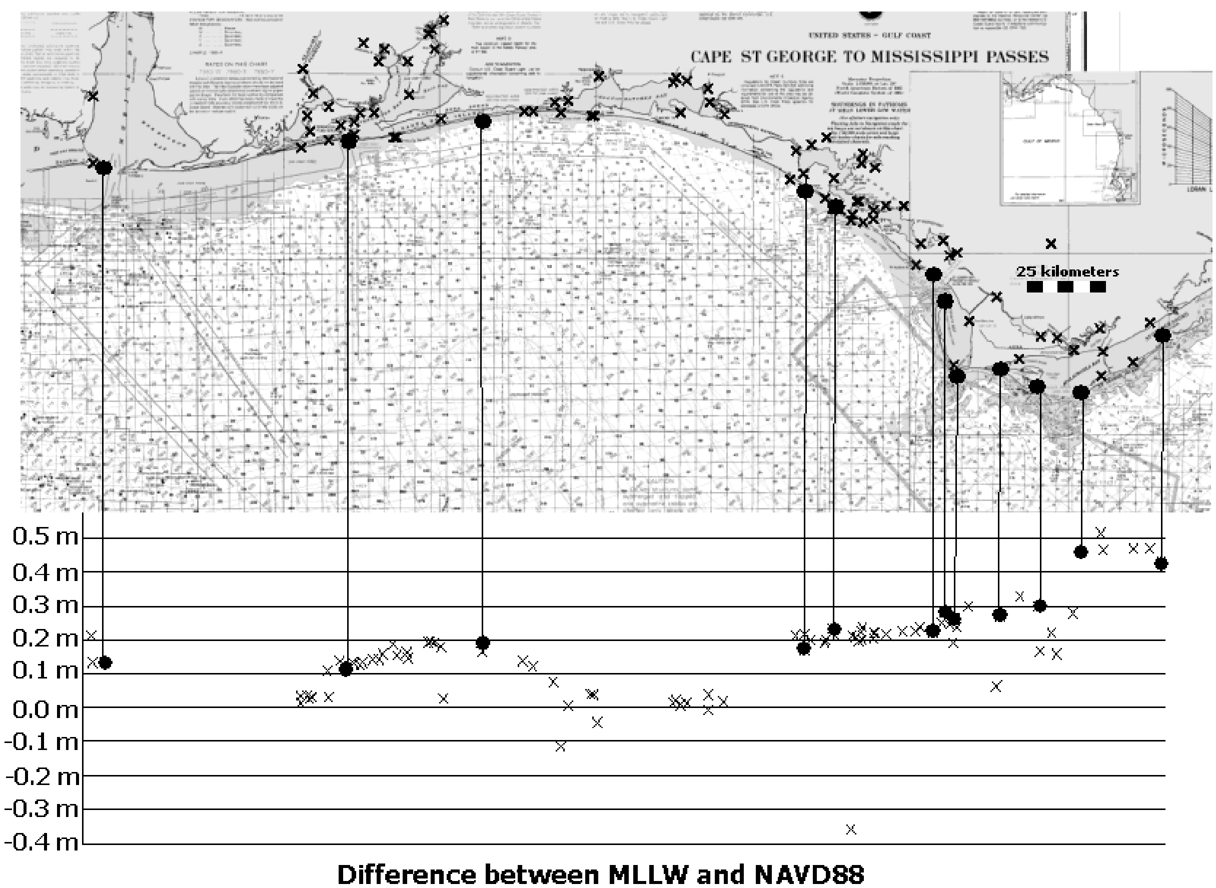

Figure 3.1 Locations of benchmarks and differences established between MLLW and NAVD88.

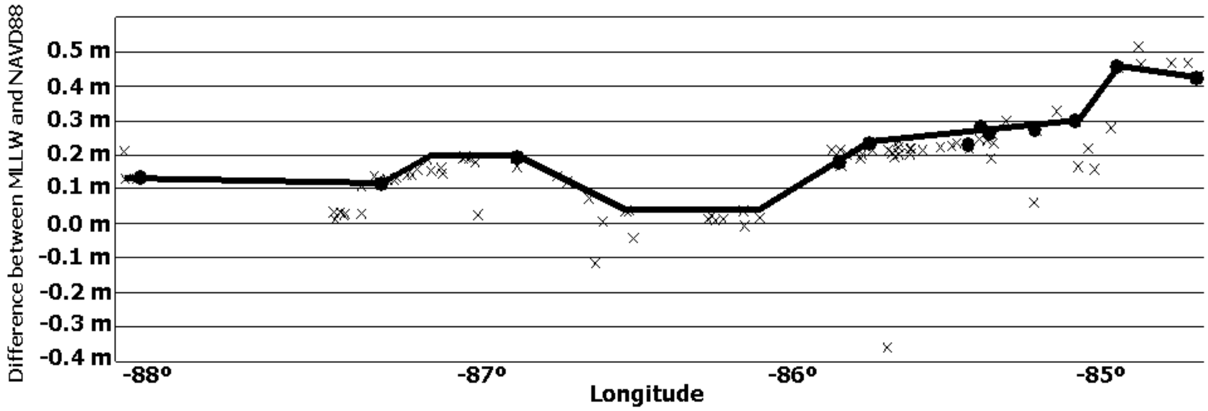

Figure 3.2 Trends determined from datum differences.

There is great variability between the datums throughout the region. The NAVD88 surface appears both above and below MLLW, as indicated by the appearance of both positive and negative numbers on the graph. This graph was used to identify trends in the datum differences. The heavy black line on the graph of Figure 3.2 shows these trends in an east-west direction by first relying on open coast benchmark values. Backbay benchmark values are used to identify trends only in absence of open coast benchmark values. Note that the points that lie a great distance from the line are in inland backbay areas where tidal dynamics are greatly altered when the tidal wave is constricted by tidal inlets.

The trends identified in Figure 3.2 were used as the basis for creating a surface of datum conversions. The surface was created using a commercial off-the-shelf digital terrain modeling package called Terramodel (Witte 1999). Shore-normal lines were drawn at each longitude where the line of Figure 3.2 changes slope. The lines were assigned a datum difference value based on the values indicated in Figure 3.2. An interpolation routine in Terramodel was used to create a surface in which the datum differences assigned to the shore-normal lines are held constant and differences are assigned between the shore-normal lines based on a linear interpolation between the lines. A datum difference was then interpolated for each point requiring datum conversion based on its geographic position using the Surface-water Modeling System (USACE 2000), a software package developed through the USACE Coastal and Hydraulics Lab. Figure 3.3 shows the vertical datum conversion surface computed for the NGDC data set.

So, each data point has a MLLW sounding value and a vertical datum conversion value that is the difference between MLLW and NAVD88 at that point.

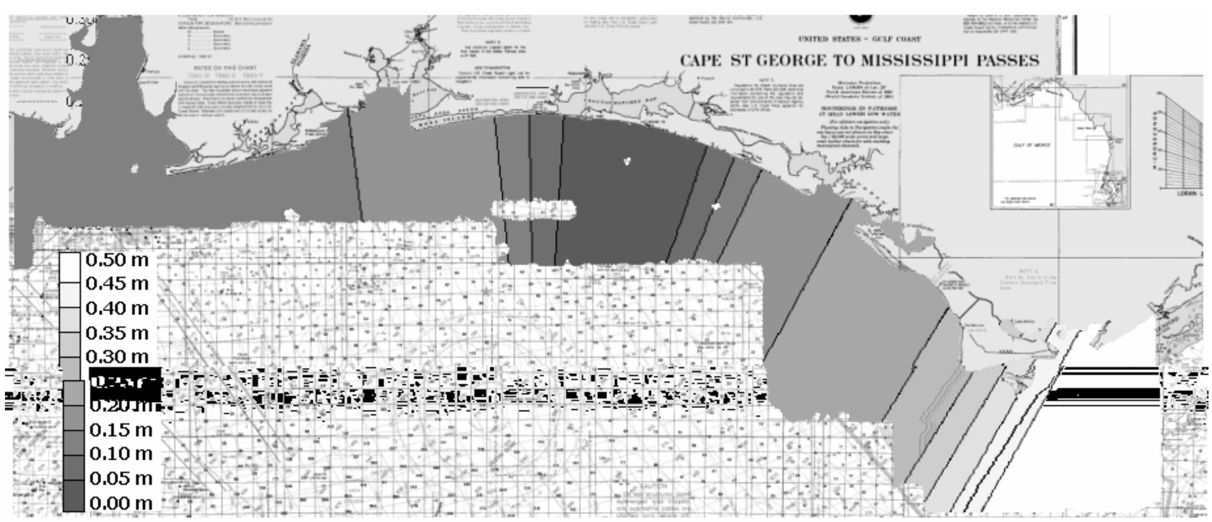

Figure 3.3 Vertical datum transformation surface for NGDC data set.

The difference is based on the vertical transformation surface created from shore-normal lines and the graph of Figure 3.2. The remaining step in the conversion is a simple subtraction of the difference between MLLW and NAVD88 from the MLLW soundings. This subtraction is logically similar to the datum conversion outlined in section 3.1 for small data sets.

3.2.2 Modeling a regional tide

The second vertical datum conversion scheme was developed to perform the conversion from MLLW to MTL. Reaching a final conversion surface required several steps: obtaining observed tidal amplitudes at a primary tide station, using a tide model to predict tides at several discrete points in the RSM region, and comparing the observations to transfer the tidal datum throughout the RSM region. Each of these steps will be described in detail in the following paragraphs.

The observed tidal amplitudes were obtained from the NOS website (NOAA 2000b) for its Pensacola, Florida, tide station. This tide station is the primary tide station for all the benchmarks in the RSM region. This means that tidal datums were established for the benchmarks based on simultaneous observations between the Pensacola station and temporary tide stations local to the benchmarks.

The observed tidal amplitudes are the verified historical record for a one-month time period beginning 1 November 1999. One month is the least amount of time recommended by NOS for transferring a sounding datum. The data obtained were referenced to MSL and local time at the gauge. A portion of this observed tidal record is shown in Figure3.4a.

The tide model ADCIRC (Westerink et al. 1992) was used to predict tides for 48 discrete points through the region. The tides are predicted relative to MTL and local time at the prediction points. Tides were predicted for the same time period mentioned above. A portion of the predicted tidal record for one of the discrete points is shown in Figure 3.4b.

There are distinct differences between the tide curves of Figure 3.4. The curves reflect the difference between actual tide measurements (Figure 3.4a) and predicted tidal amplitudes (Figure 3.4b). For example, the predicted tidal amplitudes do not include the effects of local weather like wind wave setup or storm surge. The curves also reflect the difference between a gauge in the back bay and one on the open coast. The actual tide measurements were collected in Pensacola Bay (Figure 3.4a) while the predicted tidal amplitudes were determined for a discrete point in the Gulf of Mexico (Figure 3.4b). This difference in gauge location results in variability in the arrival time and amplitude of the tidal wave between the back bay gauge and open water tide prediction location.

The transfer of a sounding datum from a primary to a subordinate tide station through the comparison of simultaneous measurements is presented in the *Computational Techniques for Tidal Datums Handbook* (NOAA 2000a). As suggested by the handbook, the modified range-ratio method is used in this study for the primarily diurnal environment of the Gulf of Mexico.

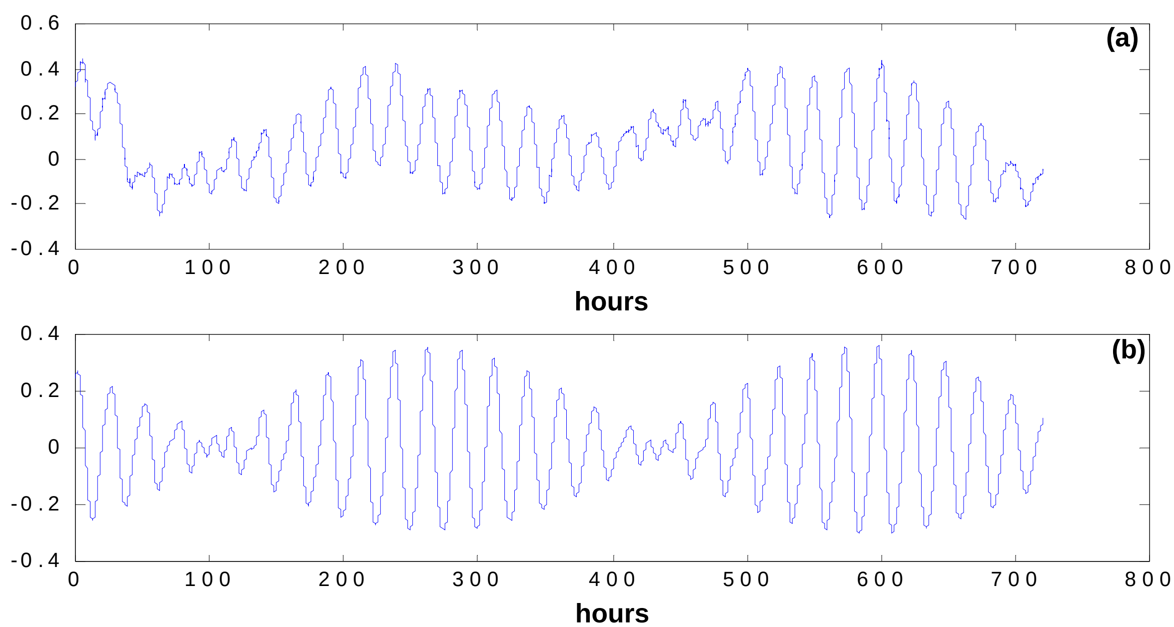

Figure 3.4 Observed and predicted tidal amplitudes. Figure 3.4a show the observed tidal amplitudes at Pensacola, Florida. Figure 3.4b shows a sample tide prediction for an offshore point.

This method tracks the time and amplitude of high tides and low tides through the month-long tidal time series. For each discrete point predicted by ADCIRC the following calculations were made: mean of high tide amplitudes, mean of low tide amplitudes, mean of high tide times, and mean of low tide times. Mean differences between the primary station and the predicted tide at each discrete point were calculated for high and low tide amplitudes and occurrences.

MLLW is established at each predicted tide station by the following equation

$$\mathrm{MLLW} = \mathrm{DTL}_{A'} - \tfrac{1}{2}\, Gt_{A'} \qquad (1)$$

where $\mathrm{DTL}_{A'}$ is the Diurnal Tide Level (DTL) at each discrete prediction point such that

$$\mathrm{DTL}_{A'} = \mathrm{DTL}_{B} + \Delta\mathrm{DTL} \qquad (2)$$

DTL_B is the accepted value for DTL published by NOAA for Pensacola, Florida (NOAAb). ΔDTL is the average amplitude difference between the gauge measurements and the tide values predicted for each discrete point.

$Gt_{A'}$ is the Great Tropic Range (*Gt*) at each prediction point such that

$$Gt_{A'} = Gt_B * Gt_{ratio} \qquad (3)$$

where Gt_B is the accepted value for *Gt* published by NOAA for Pensacola, Florida (NOAAb). *Gt* is a ratio defined by

$$Gt_{ratio} = Gt_A / (Gt_A - \Delta Gt) \qquad (4)$$

where Gt_A is the *Gt* calculated from the predicted tide values for each discrete point. ΔGt is the average difference in *Gt* between the gauge measurements and the tide values predicted for each discrete point.

The result of these calculations is a MLLW surface that is referenced to MTL. This surface is shown in Figure 3.5, along with the locations of the predicted tide stations. The stations are denoted by black dots. The datum conversion from MLLW to MTL is applied by subtracting the difference between the two datums from each MLLW sounding by interpolating a difference at each data point.

4.0 Discussion

The vertical datum conversion schemes discussed above were created using only previously collected data regarding the differences between the datums. Obviously, a tidal gauging regime tied into the geodetic benchmark system will lead to a more accurate vertical datum conversion surface. The expense of installing and maintaining conventional tide gauges may outweigh the benefits of a conversion surface based on tightly spaced gauges.

Recently, real-time kinematic GPS has been used to establish datum surfaces (DeLoach 1995, Shannon and Woodward, 1999). This technique allows collection of water level data from a floating platform (a boat or a buoy). The data are initially referenced to the ellipsoid, and can be easily transferred to a geodetic datum based on mathematical models imbedded in software like GEOID99 (NOAA 2000d). Tidal datum information is derived by the simultaneous observation methods described above.

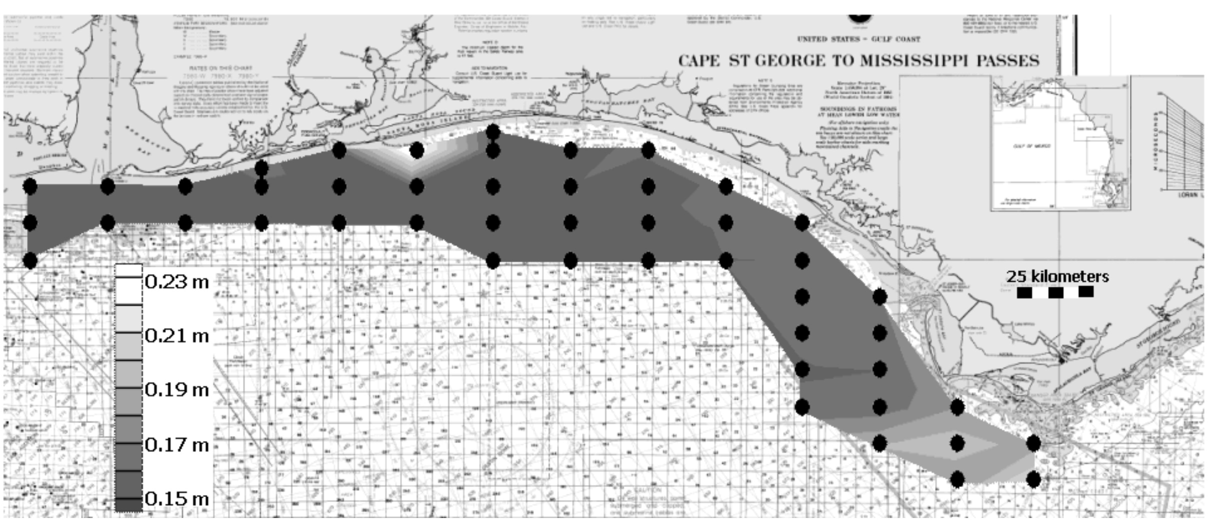

Figure 3.5 Vertical datum conversion surface based on modeling a regional tide.

Though this new method can reduce the cost of determining tidal datum surfaces relative to the ellipsoid, a rigorous measurement scheme should be developed to eliminate the additional costs of redundant measurement. In the case of the RSM Demonstration Program, some information regarding the placement and spacing of gauges can be derived from the creation of a datum surface for the vertical datum conversions.

For example, the data shown in Figure 3.3 indicates that measurements be made in each of the trapezoidal shaped zones defined by the black contour lines. This would ensure that the resulting conversion surface had an accuracy of 0.05 m, which is the contour interval. In conjunction with this information, Figure 3.5 suggests additional measurements at the eastern side of the region are needed. Though the differences in this datum surface are small (.08 meters for the entire region), there is an indication of changing tidal dynamics at the eastern end that should be investigated.

Additional information that should be considered is the relative change of a datum surface within a region. Figure 4.1 shows the NAVD88 surface relative to the GRS80 ellipsoid in 0.5 meter contours. This information suggests possible offshore spacing for new tidal measurements. These contours are based on values obtained from Corpscon (TEC 2000).

Relative changes in a tidal datum surface could come from the phase and amplitude change recommendations for zoning of tide reducers for survey data. NOS requires that any changes in time of arrival of the tidal wave greater than 0.3 hours, or any difference in amplitude greater than 0.06 meters be reflected in the zoning scheme for application of tide reducers (NOAA 1999). This information can be obtained by cophase analysis using Fourier transform techniques. An example of this type of analysis is shown in Figure 4.2. It is based on the same data used for the comparison of simultaneous observations, except the record length was extended to four months. Figure 4.2a shows the phase, or time difference between the gauge at Pensacola and each of the tide prediction stations. Figure 4.2b shows the multiplier required to match the amplitude of the Pensacola gauge at each of the tide prediction stations. The multipliers are the means of multipliers required for each of the 6-minute predictions to match the 6–minute observations. For this calculation, the predicted values are shifted in time based on the phase information from the cotidal analysis. These two figures also indicate changes in tidal dynamics at the easternmost portion of the RSM region. The contour plot of multipliers show additional areas of change at the center and westernmost portions of the RSM region as well.

5.0 Conclusions

The vertical datum conversion schemes derived above meet the criteria of seamless conversions for densely spaced data and for using sparse data to create a realistic conversion for a large area. Linear interpolation of sparse datum information provides a successful means to convert between tidal and geodetic datums. A tide model can assist in converting between tidal datums by transferring the datum using the concept of comparison of simultaneous observations. Guidelines for the placement of conventional tide gauges can be obtained based on the variability discovered when creating vertical datum conversion surfaces for a large region. Additional information can be obtained through traditional methods such as vertical datum conversion software and cophase tidal analysis.

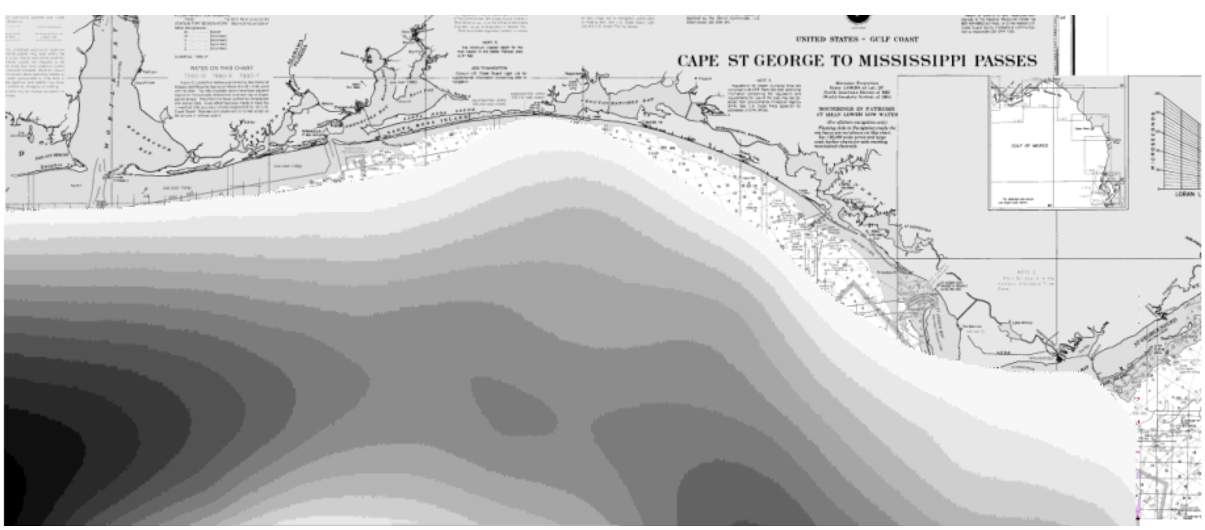

Figure 4.1 NAVD88 surface relative to the GRS80 ellipsoid (0.5 meter contours).

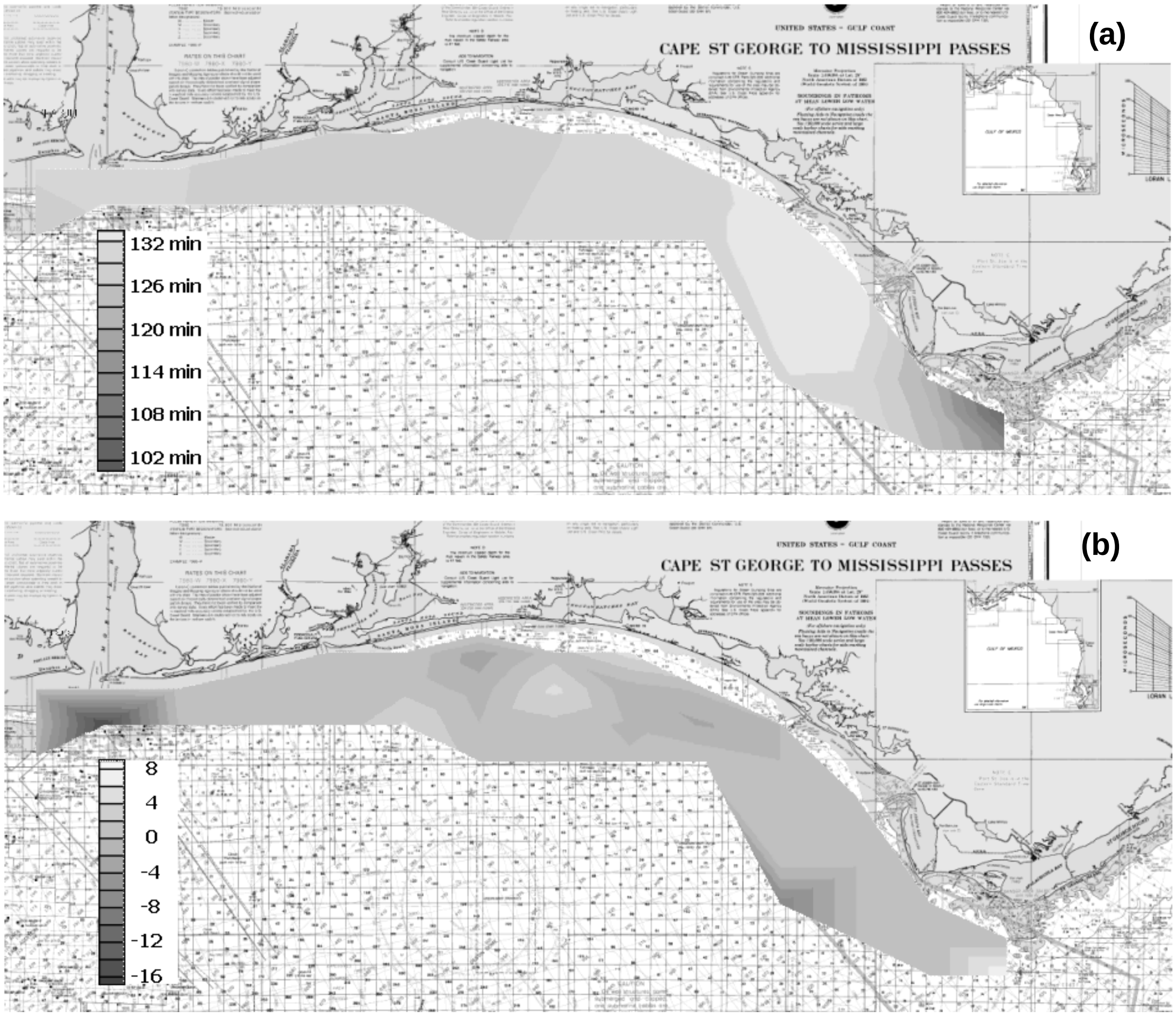

Figure 4.2 Phase difference and amplitude multipliers determined for Pensacola, Florida, tide gauge and tide prediction stations. Figure 4.2a shows the phase difference in minutes. Figure 4.2b shows the multiplier required to transfer measurements from the Pensacola gauge to the tide prediction stations.

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Acknowledgements

Unless otherwise noted, the work presented herein was funded by and performed at the U.S. Army Corps of Engineers, Mobile District, Joint Airborne Lidar Bathymetry Technical Center of Expertise. The use of trade names does not constitute an endorsement by the U.S. Government.